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SEA CACHE: A MOBILE PETROLEUM, OILS, LUBRICANTS SEAFLOOR STORAGE AND SUPPLY SYSTEM FOR ADVANCED BASES

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The structural and operational characteristics of a mobile POL (petroleum, oils, lubricants) logistics system are presented. The system, called SEA CACHE, is based on using large (224' long x 64' wide x 24' high) prestressed concrete structures to transport and store up to 27,000 barrels of POL product. Transport of the POL filled structures is by surface tow and storage is on the seafloor in water depths to 600 feet. The system can

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operate in conjunction with military forces at advanced bases where the seafloor structure is emptied via pipeline to the beach. In this manner, many of the hazards associated with on-land storage of POL are avoided. The structural and operational analyses show that this system is feasible and is a logical approach to meeting the military's advanced base POL requirements of today and of the future.

INTRODUCTION

Military requirements for POL (petroleum, oils, lubricants) have increased rapidly over the past decade as force mobility has increased. In World War II, 50% of the logistic supply tonnage going to troops overseas was POL products. Estimates indicate that during the Vietnam conflict this figure jumped to 70% of the tonnage supplied and was rising [1]. This means that those military units charged with the logistic supply of combat forces must center more attention on POL-related systems to meet demands. Factors such as the continual increase in tonnage required, strategic doctrines that emphasize force mobility, and the loss of foreign bases make it more difficult to meet POL requirements. New concepts must be considered to meet these requirements.

Sea Cache is a new POL storage and supply system that places emphasis on operation from the seafloor and is compatible with anticipated military needs and modes of operation. The objective of this report is to present the Sea Cache system by discussing its operational modes and by presenting a preliminary design for the POL Sea Cache structure.

BACKGROUND

Supply of POL to our troops at advanced bases is currently achieved by off-loading moored tankers via a pipeline to the beach. The POL coming ashore from the tanker is stored in, and distributed from, advanced base POL facilities such as the Marine Corps Amphibious Assault Fuel System (AAFS) or the Army Tactical Marine Terminal (TMT). This approach to POL supply has become unsatisfactory because of rising concerns for system security, mobility, and capacity that result from changing military operational concepts.

Alternatives to the tanker/pipeline system are being examined. Landing craft and lighters have POL transport capabilities that have been utilized occasionally. However, the relatively low storage capacity and high vulnerability of these vessels make them less than ideal candidates for the POL transport and supply mission. Helicopters and air-cushion vehicles have also been considered. These vehicles have high speed capabilities, but they use large quantities of fuel and have limited cargo capacities.

Two new alternative POL supply concepts have evolved recently; one concept uses POL-filled LASH barges and the other concept uses flexible bags. The LASH barge concept utilizes LASH ships to transport the barges to an operational site where they are off-loaded and moored offshore. As needs for the POL develop, the barges would be beached and unloaded; or they would remain offshore and be unloaded via hoses to the beach. Each LASH barge has a capacity of 2,400 barrels (100,000 gallons). The flexible-bag concept would use conventional ships to haul stored collapsible bags to the operational site where they would be off-loaded, filled by a tanker, and emptied via hose to the beach. Both of these systems have increased mobility over static on-land storage systems, but both require a mooring system and are quite vulnerable to enemy action.

One of the most promising ways to achieve high storage capacity and improved security, plus system mobility, is by using submerged offshore storage structures. If a large tank were devised that could be positioned on the seafloor, the POL products could be brought ashore via a submerged pipeline. In this way, onshore storage of POL would be minimized while still utilizing the well-developed on-land distribution systems. The result would be a system where POL products are in a concealed environment with minimum fire hazard and vulnerability to enemy action. Because of the potential of such a system, both the Navy and Army have examined seafloor POL storage and supply. The Navy sponsored a study [2] to examine the feasibility of using flexible containers as submerged 1,200-barrel (50,000 gallons) fuel caches. It was apparent from the study that the large buoyant force of the POL-filled structure produced severe anchorage problems and high stresses in the container wall. To overcome these problems, a complicated steel framework was required to restrain the flexible container on the seafloor.

An Army study [3] determined the feasibility of a 50,000-barrel, rigid, steel tank for underwater storage. This study concluded that the rigid tank was feasible for deployment depths up to 200 feet. The system was well received at the time even though it was somewhat inflexible in operational capabilities; however, during the development period, a lack of firm mission requirements for underwater storage caused the concept to be shelved.

The present Sea Cache concept includes the following improvements over the Army system: (1) a greater percentage of the volume of the structure is used to store POL, (2) the installation method is more rapid, (3) no auxiliary anchoring system is required for structure stability on the seafloor and (4) the initial cost of the structure is approximately 10% less expensive per barrel of stored POL.

POL SEA CACHE SYSTEM

Description of System

The Sea Cache System is based on using a large prestressed concrete structure to store 27,000 barrels of POL on the seafloor. The structure is comprised of two cylindrical tanks connected together by a bottom and top deck (Figure 1). The volume of the center section enclosed by the decks is equal to the volume of one cylindrical tank. The structure is 24 feet high, 64 feet wide, and 224 feet long. Bulkheads across the structure are spaced at 28-foot intervals along its length; this divides the structure into eight sections. The structure is fabricated of prestressed concrete for several reasons: (1) the strength of prestressed concrete enables the structure to resist hogging and sagging caused by conditions encountered on the sea surface; (2) the strength of concrete in compression enables the structure to resist the hydrostatic pressure loads encountered during descent; and (3) the mass of concrete supplies the necessary weight for a highly negatively buoyant structure on the seafloor. Other significant advantages of using concrete are its excellent durability in seawater (which means long life and low maintenance [4] for the structures), and the economy of fabricating a structure of concrete compared to other construction materials.

The structures are towed empty over long distances at speeds up to 13 knots. When the structures reach the vicinity of their deployment site, a tanker fills each structure with 27,000 barrels of POL. A full load of POL fills both tubes of the structure; the center space remains empty for towing on the surface. Because the structure is compartmentized, more than one type of POL can be stored. For a full structure, tow speeds up to 10 knots can be achieved using an ocean-going tug.

Once at the deployment site, the structure will be installed on the seafloor as rapidly as possible; this operation is estimated at 3 to 4 hours. It is desirable to install the structure in water depths greater than 250 feet but not greater than 600 feet.

The first step in structure deployment is to open valves in one of the tanks (Figure 2a) and allow POL to flow by gravity into the center space. The structure will rotate so the empty tank is on top (Figure 2b). Next, a flexible pipeline is attached to the structure. The structure is then made negatively buoyant by a maximum 200 kips by allowing seawater to enter selected compartments along the empty tank. If light POL is the cargo, approximately five compartments will be filled with seawater; if heavy POL is the cargo, approximately two compartments will be filled. The structure is ballasted in such a manner that a stable tilted position is attained (Figure 2c). The structure is then lowered to the seafloor using the tow cable, thereby saving time required to rig a special lowering line. As the structure approaches the seafloor, its rate of descent is reduced. At touchdown, impact forces are dampened because the structure pivots on the front-end contact point. This installation method is rapid because the cylindrical tank sections are strong enough to resist external hydrostatic loads down to a depth of 600 feet. The center space is not pressure resistant, but is vented to the seawater environment and, therefore, is pressure-compensated. Compressed air is not required to counter hydrostatic loads on the structure as was the case with the Army concept [3]; this saves considerable time during implant. On the seafloor, solenoid valves are opened in the empty tank compartments so that they flood with seawater (Figure 2d). Now the highly negatively buoyant structure rests on the seafloor with bearing pressures that range from 1.5 to 2.4 psi for light and heavy POL, respectively. These bearing pressures are sufficient to self-anchor the structure. However, if the structure should be placed at depths less than 250 feet and large surface waves were to be generated from storms, there is the possibility that the structure would move horizontally on the seafloor. Hence, it is desirable to remain at depths lower than 250 feet where the effect of surface waves on the structure is small.

To extract POL from the structure, solenoid valves are opened which permit POL to move up the pipeline. Since the POL has a lower specific gravity than seawater, a pressure differential is created in the structure-pipeline system that is used to ''pump'' the POL to shore. At a depth of 600 feet, light POL will flow unassisted through 5,000 feet of 6-inch pipe at a rate of 600 gpm. To maintain this flow rate for longer lengths of pipe or for heavy POL, pumping is required.

As POL is removed from the structure, seawater will enter so that the structure remains full at all times. Completely filled, submerged structures are quite resistant to damage from underwater explosions.

To avoid contamination of POL with seawater, a flexible membrane separates the two liquids. Figure 1 shows the location of the membrane and its method of operation. Seawater is prevented from permeating the concrete wall by an epoxy waterproof coating on the exterior concrete surface and by the POL, which is at ambient pressure, and is forced into the voids in the concrete on the inside wall. Thus, POL will saturate the concrete and prevent seawater from contaminating the stored POL.

Retrieval of the structure from the seafloor involves making the structure buoyant so that it can rise to the surface. The pipeline to the shore can deliver compressed air to the structure. Seawater will be displaced by the compressed air and the structure can be made buoyant within a wide range of values because any number of compartments in the structure can be cleared of seawater. In the case of one tube being blown free of seawater, the structure will remain negatively buoyant by 300 kips, but the moment arm between the center of gravity and center of buoyancy will cause the structure to rotate and, thus, break out of a mud bottom. This will occur if a long enough time period, in terms of days, elapses.

For breakout in a short period of time (hours), the buoyancy required for breakout from the worst settlement condition of 14.5 feet is approximately +900 kips. This buoyancy can be obtained by blowing one tube and two compartments in the center section. If both a tube and the entire center space are blown completely free of seawater, the net positive buoyancy is 3,780 kips.

Once the structure is positively buoyant and has broken out of the seafloor, it will freely ascend to the surface. As the compressed air expands during ascent, one-way valves will vent the excess air pressure and, thus, a constant buoyancy will be maintained. Once the Sea Cache structure is on the surface, the remaining seawater can be blown. The structure is now ready for a new POL supply assignment.

Operational Concepts

Pre-positioned Concept. Sea Cache structures can be placed on the seafloor at world locations selected for the proximity of the site to potential U.S. military involvement. The structures store POL in protected harbor areas or on the continental shelf in water depths to 600 feet. The cache represents a reservoir of POL products that can be mobilized quickly for transport to advanced bases or can be tapped for resupply of fleet vessels during crisis.

If immediate U.S. military actions are required, Sea Cache structures can be refloated in a matter of hours and a ship of opportunity can tow the POL cargo to the advanced base. Assuming the distance of tow is 500 miles, the POL supplies would be on-site in less than three days using a tow speed of 10 knots. This time frame is compatible with troop build-up and is faster than the present POL supply system which requires a tanker to be located, to return to port, to be loaded with the appropriate POL products, and then to run to the advanced base, a procedure which is estimated to take from 5 to 10 days.

Direct Transport Concept. The direct transport concept only considers the Sea Cache System as an advanced base POL storage and supply system. In this operational mode, it is most important to get Sea Cache structures to the advanced base as quickly as possible. Several approaches can be taken to achieve this objective:

1. Surface tow from CONUS, fully loaded. A Sea Cache structure that is fully loaded with the heaviest POL product, diesel fuel, can be towed at 10 knots by a 6,000-hp tug. This speed is relatively slow when compared to tankers that operate at 15 to 20 knots. The Sea Cache structures are not a competitive system in this operational mode.

2. Submerged tow, fully loaded. It is feasible to tow the Sea Cache structures in a submerged condition. A paravane would be required to control the depth of the structure during tow. Less drag may be experienced during a submerged tow because wave effects are eliminated; hence, an increase in tow speed is possible. An important additional consideration is that covert transport of POL may be possible.

3. Surface tow, empty. The main purpose of the structures is seafloor storage and supply of POL; hence, for maximum speed the structures should be towed to the advanced base in an empty condition. The point of origin could be from any allied country, not necessarily CONUS, because these concrete structures can be fabricated worldwide. Once the structures are near the advanced base, they could be loaded with POL via tankers and then towed to their deployment site. This mode of operation is recommended.

COMPATIBILITY OF SEA CACHE WITH PRESENT AND PROPOSED SYSTEMS

The POL Sea Cache System fits into the military system in a manner that minimizes new hardware purchase or development, the retraining of personnel, or the development of new military tactics or modes of operation. To illustrate the compatibility of the Sea Cache system, some current and proposed POL logistics systems of the Marine Corps and the Army will be examined with respect to the Sea Cache system.

The USMC Amphibious Assault Fuel System (AAFS)

The Marine Corps has an operational system designed for short term use in an assault environment; this system is the Amphibious Assault Fuel System (AAFS) [5]. The AAFS consists of a beach unloading station, two booster stations, two dispersion units, and five tank farms. The beach unloading station receives incoming fuel from tankers, LST's, tank trucks, or drums and pumps it into two holding tanks or to inland booster stations. The booster stations pump the incoming POL products to the tank farms or dispersing units. The five tank farms are the storage units of the AAFS with a total capacity of 14,300 barrels stored in 36 flexible tanks. The dispersion units filter and monitor the quality of the POL products and disperse the products to the user or to a secondary transport system. The most unsatisfactory component of the AAFS from an endurance, repetitive use and operational standpoint is the flexible POL storage tanks. These tanks are extremely vulnerable to attack, are time consuming to place because of the protective earth berms needed for each tank, and require large land area for protective tank dispersion. In addition, the Marine Corps Bulk Fuel Company, which can operate eight of these fuel systems, has been shown to be 10 to 50% under capacity for the projected 10-day fuel volume requirements of the Marine Amphibious Force (MAF), a unit supplied by the AAFS [6].

If the flexible tanks of the AAFS were to be replaced by a single Sea Cache structure, the safety of the POL products in storage would be increased, the time and effort needed for the erection of the on-land components of the AAFS would be reduced (the volume and weight of on-land equipment would be reduced by more than 20%), and the storage capacity would be increased from 14,300 to 27,000 barrels. In addition, several types of POL could be supplied from a single structure. The only negative feature of the Sea Cache/AAFS combination lies in the reduced control the ashore personnel have over the stored POL products.

To summarize, meshing the Sea Cache concept with the AAFS would result in a system that increases the capabilities of the AAFS while utilizing most of the presently used on-land hardware and minimizing the retraining of AAFS personnel.

U.S. Army Tactical Marine Terminal (TMT)

The Tactical Marine Terminal (TMT) is the Army's rapid response POL supply system and is now under development [7]. The TMT consists of a system for mooring tankers offshore, hoselines to bring the POL products ashore, shore storage in flexible tanks (forty-two 1,200-barrel tanks), and manifolding, pumping, and dispensing units to get the bulk products from storage to the consuming equipment or to a secondary transport system. In all, the components and operational modes of the TMT are very similar to those of the AAFS except that the operational TMT uses its own equipment to off-load tankers, has a 90-day minimum operational endurance limit, and has a storage capability of 50,000 barrels (3.5 times that of the AAFS).

As with the AAFS, Sea Cache structures can replace most of the on-land flexible tanks in the TMT and can produce a system which will utilize the remaining hardware in the system. Two POL Sea Cache structures would provide 54,000-barrel storage capacity and would eliminate near-shore refilling operations, a situation that places the tanker in jeopardy.

To summarize again, the POL Sea Cache system can provide the necessary storage capacity in a secure environment on the seafloor and can eliminate the need for off-loading tankers close to shore.

U.S. M.C. Seaborne Mobile Logistics System (SMLS)

A Marine Corps concept for the supply of troops in future operations at advanced bases is called the Seaborne Mobile Logistics System (SMLS). This system centers around a fleet of specially configured ships which would supply all items needed by the forces ashore by using V/STOL aircraft to transport the supplies.

Two problems have arisen with this system that can at least be partially alleviated by including the Sea Cache system in the SMLS concept. One problem is that the SMLS supply ships could withdraw, leaving the support of troops ashore in doubt, if enemy action threatens the ships' safety. If POL products were at least partially supplied by the Sea Cache system, the chances for a continuous flow of POL would be increased. A second problem is that the aircraft envisioned for air-lifting the supplies, including POL products, are themselves high users of POL products. For example, if the line of communication between the ships and the troops is 500 miles or more, the aircraft burn more fuel than they can deliver. If the majority of the POL products needed by the troops were supplied by Sea Cache, the cargo tonnage burden on the SMLS system could be reduced by more than 50%.

The negative features of the Sea Cache/SMLS combination lie in the fact that the SMLS fleet would be made up of high-speed ships with cruising speeds in excess of 20 knots. The Sea Cache system cannot match these speeds under the best of conditions. However, with proper planning, the Sea Cache System could still supply a large portion of the POL. Secondly, the SMLS-supplied POL products can be delivered to in-land sites and not just to the beach as is the case with Sea Cache. This shortcoming could be eliminated by supplying POL to the beach via the Sea Cache system where it would be carried by the V/STOL aircraft to in-land distribution points. This interaction between systems could make the delivery of POL products more independent of the actions of the SMLS fleet and could greatly reduce POL consumption by the V/STOL aircraft.

MOBILITY OF SEA CACHE

In the past few years, the strategic doctrine of the United States has shifted from an emphasis on our nuclear superiority to a reliance on mobile, forward-deployed, amphibious forces to deter crisis and project U.S. influence [8,9]. The logistics systems that supply amphibious forces must be as mobile and responsive as the forces they supply. The POL Sea Cache System is mobile in that the structures can be prepositioned, towed to areas of need, and transported from place-to-place to reflect tactical planning within an operational area.

PRELIMINARY DESIGN

The preliminary design for the POL Sea Cache System consisted of studying its major features to determine whether or not the system could be made operational. The preliminary design went into detail only as far as necessary to demonstrate feasibility. It was determined that the system was completely within the state of the art and feasible.

Configuration

The overall configuration of the Sea Cache structure is shown in Figure 1. The structure, fabricated of prestressed concrete, is 224 feet long, 64 feet wide, and 24 feet high. In cross section, the structure appears as a double-barreled tube where two cylindrical tubes, each with an outside diameter of 24 feet and wall thickness of 14 inches, are connected by a top and bottom deck. The spacing between the tubes is such that the volume of the center section is equal to one tube. Along the length of the structure, bulkheads are spaced at 28-foot intervals to divide each tube and center section into eight compartments. Hemispherical end closures cap the tube sections because the tubes must withstand hydrostatic pressure loads.

Concrete as the Construction Material

Concrete was selected as the construction material for the structure, not by choice, but by necessity. The POL Sea Cache System requires that the structure with a full load of POL must have a wide range of buoyancy values (which will be discussed in the section Structure Weight, Buoyancy, and Cargo Weights) from positive buoyancy to float on the sea surface to highly negative buoyancy for stability on the seafloor. At the same time, the structure must be capable of resisting the hydrostatic pressure loadings on the seafloor. These requirements eliminated metals as potential, economical construction materials. Concrete fulfills the weight requirements, and recent advancements in the state of the art have shown that concrete is well suited as a construction material for pressure-resistant structures [10,11,12].

The performance of concrete as a marine construction material has been excellent whenever high quality concrete has been used. Concrete submerged partly or totally for up to 67 years in seawater has been found to maintain its structural properties [13]. Most pertinent to this study is the recent completion of the Ekofisk structure (Figure 3) which is a concrete crude oil storage tank for the North Sea [14]. Six other concrete structures for oil drilling, production, and storage are under construction in Norway for operation in the hostile North Sea. These structures demonstrate that concrete has gained the acceptance of the offshore oil industry as a construction material for the ocean.

Construction Feasibility and Cost

Construction of the POL Sea Cache Structure is entirely feasible. A submerged oil storage system proposed by Santa Fe-Pomeroy, Inc.* uses a concrete structure of similar configuration to the Sea Cache concept; this structure presents no unusual construction problems. The fabrication approach would be to use precast segments of a double-barreled shape and assemble the segments into a long structure by post-tensioning methods.

Ameron Corporation (a concrete pipe manufacturer) presently fabricates pipe having an outside diameter of 20.5 feet and a length of 20 feet (Figure 4). These pipe sections are joined together in the field for the construction of aqueducts.

The cost of a Sea Cache structure when several are fabricated is estimated at $840,000. Table 1 shows a cost breakdown for the structure. In different terms, the Sea Cache structure costs $31.00 per barrel.

As a cost comparison, the Army's submerged POL-storage tank was estimated to cost $724,000 in 1961 or an adjusted present-day (1974) cost of $1,500,000. The storage capacity of the barge was 50,000 barrels of light POL or 38,000 barrels of heavy POL; this gives a per barrel cost of the structure as $30.00 barrel when carrying light POL or $39.40 when carrying heavy POL (average cost $34.70). Hence, the Sea Cache

*The Santa Fe-Pomeroy concept used a double-barreled structure as a fixed seafloor structure to store 200,000 barrels of crude oil. It differs from the Sea Cache concept in that Sea Cache can transport POL and can be rapidly deployed to the seafloor as a pressure-resistant structure.

structure at \$31.00 barrel for light and heavy POL is approximately 10% less expensive than the Army concept.

Table 1. Cost Estimate for Sea Cache Structure

Item	Quantity	In-Place Unit Cost	Cost
Concrete	2,400 yd^3	\$100/yd^3	\$240,000
Prestressing steel	370,000 lb	\$1.00/lb	\$370,000
Reinforcing steel	175,000 lb	\$0.40/lb	\$ 70,000
Separation membrane	12,000 ft^2	\$2.00/ft^2	\$ 24,000
Exterior epoxy coating	36,000 ft^2	\$1.00/ft^2	\$ 36,000
Plumbing	-	-	\$100,000
Total	-	-	\$840,000

Structure Weight, Buoyancy, and Cargo Weights

Dead Weight (DW) of Structure:

DW of each tube = cylinder + ends + bulkheads
= 2,580K + 290K + 220K = 3,090K

DW of center = decks + bulkheads + plumbing
= 3,170K + 360K + 100K = 3,630K

DW of structure = tubes + center
= 2(3,090K) + 3,630K = 9,810K

Displacement (D) of Structure:

D of each tube = cylinder + ends
= 5,790K + 460K = 6,250K

D of center = decks = 6,500K

D of structure = tubes + centers
= 2(6,250K) + 6,500K = 19,000K

Net Buoyancy (B) of Structure:

B of each tube = D of tube - DW of tube

= 6,250K - 3,090K = 3,160K

B of center = D of center - DW of center

= 6,500K - 3,630K = 2,870K

B of structure = D of structure - DW of structure

= 19,000K - 9,810K = 9,190K

Cargo Weights. Four types of POL are required at advanced bases: aviation gasoline, automotive gasoline, jet fuel, and diesel oil. For design purposes, the widest spread in specific gravities between these POL products are required. The lowest specific gravity is obtained from gasoline at an assumed maximum temperature of 86°F; this specific gravity is 0.6886. The highest specific gravity is obtained from diesel oil at an assumed minimum temperature of 30°F; this specific gravity is 0.8871 [3]. Table 2 summarizes the cargo weights, resulting buoyancy, draft, and freeboard for structure.

Table 2. Structure Under Different Cargo-Loading Conditions

Cargo Loading Condition	Density of POL (lb/ft^3)	Cargo Weight (kips)	Buoyancy of Structure (kips)	Draft (ft)	Freeboard (ft)
Empty	0	0	9,190	12.5	11.5
Full, Light POL	42.0	6,350	2,840	19.6	4.4
Full, Heavy POL	55.4	8,376	814	22.6	1.4

Structural Analysis

Bending. The principle of prestressing applied to concrete allows a concrete structure to experience flexural loading conditions without the concrete material being stressed into tension. By using pre- or post-tensioning steel wires, concrete can be placed in a state of residual compression. The magnitude of the compressive stress needs to be great enough to absorb tensile stresses generated by service loads. To determine the magnitude of prestress for the concrete, one needs to calculate the expected maximum tensile stress which a non-prestressed structure would experience and then induce a compressive stress of equal magnitude within the concrete.

The tensile stresses developed from service conditions are calculated by determining the maximum sagging and hogging moments on the structure. The moments are converted to stresses, and the prestress force is then determined. Table 3 summarizes the maximum moments and stresses. The highest tensile stress is 1,910 psi and is caused by a hogging condition in the longitudinal direction when the structure is loaded with heavy POL. The highest tensile stress in the transverse direction is 140 psi. Hence, the structure must be prestressed to -1,910 psi* in the longitudinal direction and -140 psi in the transverse direction; these levels of precompression for the concrete are well within the state of the art. Under extreme service conditions the maximum stresses in the wall in the longitudinal direction will be 0 and -3,820 psi, and in the transverse direction they will be 0 and -280 psi.

The concrete compressive strength can now be determined because the maximum working stress has been defined as -3,820 psi. The working stress should not exceed 0.45 of the compressive strength of the concrete [15]; therefore, the uniaxial compressive strength of 6 x 12-inch concrete control cylinders should be 3,820/0.45 = 8,500 psi at the time the structure undergoes service conditions.

The factor of safety against failure for the structure on the sea surface will be two. The desirable failure mode is for tensile crack development and yielding of reinforcement before crushing of concrete.

Concrete Cracking. Cracking of concrete due to tensile stresses will not be permitted. Under maximum service loads, the structure does not experience tensile stresses. The limiting tensile capacity of the concrete is the modulus of rupture and is equal to $7.5\sqrt{f'_c}$ = 690 psi [15]. Thus, the structure can experience considerable loads in excess of the design maximum moment before the concrete will crack.

Shear. The shear capacity of prestressed concrete is controlled by the principal tensile stress in the concrete. The American Concrete Institute (ACI) Code limits prestressed concrete sections under shear loading to the permissible principal tensile stress of $4\sqrt{f'_c}$ = 370 psi. The maximum principal tensile stress, calculated from a combined stress equation [16] that accounts for biaxial compressive and shear stresses, is 140 psi. Hence, the factor of safety against shear failure is 370/140 = 2.6.

Fatigue. The fatigue resistance of the prestressed concrete structure to sagging and hogging conditions is high. Fatigue in prestressed concrete is not a significant problem if stress reversals are avoided and if the level of compressive stress remains less than the maximum allowable working stress. Fatigue failure of steel prestressing strands is highly improbable because the stress variation in the strands is negligible under service conditions.

*The minus sign means compressive stresses.

Pressure Resistance. During installation of the structure on the seafloor, the cylindrical tanks will resist the full hydrostatic pressure load (the center section will be at ambient pressure). The pressure-resisting capability of the concrete structure was calculated using the empirical equation given in Reference 12. This equation is:

$$p_{im} = (2.05\ t/D_o - 0.028)\ f'_c \tag{1}$$

where p_{im} = implosion pressure (psi)

t = wall thickness (inches)

D_o = outside diameter (inches)

f'_c = concrete compressive strength (psi)

Substituting the appropriate values for the Sea Cache structure into Equation 1 yielded an implosion pressure of 609 psi or pressure head of 1,370 feet.

To obtain an operational depth, the implosion pressure head was multiplied by 0.45. This procedure is similar to following the ACI Code to obtain the working stress for concrete. Hence, the operational depth is 0.45 (1,370) = 616 feet; say 600 feet.

The prestress force in the steel strands is relieved at the depth of 600 feet; hence, the maximum operating depth is not influenced by the fact the structure is prestressed concrete.

Settlement

Upon initial contact with the seafloor, the structure will experience short-term settlement and will settle to a depth at which the bearing pressure exerted by the structure equals the bearing capacity of the soil. With time, the structure will experience long-term settlement. A typical weak mud bottom soil was used in this analysis. The rate of soil strength increase with subbottom depth is represented by a c/p ratio of 0.35. (c is the undrained shear strength of the soil and p is the effective soil pressure). The structure acts like a large flat plate with an assumed bearing width of 55 feet and length of 200 feet.

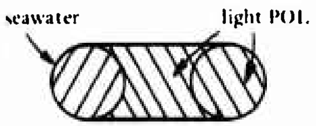
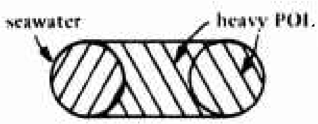
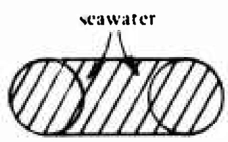
Table 4 shows settlement data for three loading conditions on the structure. The analysis did not account for the nonuniform distribution of bearing pressures. The short- and long-term settlemment analysis was conducted by Lee [17]. The maximum settlement was 14.5 feet in weak mud. In sand, the total settlement would be about 2.0 feet. None of these settlement conditions will cause problems during operation or during retrieval of the structure.

Table 3. Maximum Bending Moments and Stresses

(Cargo load condition: full load of heavy POL)

Condition	Moment (kip-ft)	Stress (psi)
Longitudinal sagging	410,000	1,520
Longitudinal hogging	514,000	1,910
Transverse sagging	78,500	100
Transverse hogging	104,900	140

Table 4. Settlement of Sea Cache Structure

Case	Average Bearing Pressure (psf)	Settlement*		
		Short Term (ft)	Long Term (ft)	Total (ft)
	212	4.0	4.0	8.0
	345	6.6	4.6	11.2
	497	9.5	5.0	14.5

*Settlement results are for a weak mud bottom soil.

On-Bottom Stability

A problem encountered by any large seafloor structure is the instability of the structure caused by surface waves. Long period surface waves produce lift and drag forces that reach to hundreds of feet of depth. The Sea Cache System was designed to be stablized by gravity forces and not require ancillary anchorage systems. This was accomplished by designing Sea Cache to be highly negatively buoyant and to have a low profile configuration.

For analysis purposes, the structure was assumed resting on a sandy bottom where settlement and breakout resistance would not aid in resisting uplift and horizontal drag forces. On-bottom stability of the Sea Cache structures was evaluated using analytical techniques developed in Reference 18.

To illustrate the on-bottom stability of the Sea Cache structure, suppose a structure filled with light POL were exposed to a sea state 6 wave environment (significant wave height = 13 feet, maximum wave length = 560 feet) when installed at a depth of 250 feet with the structure's long axis parallel to the passing waves. The maximum wave-induced lift force exerted on the structure would be 730 kips. Since the submerged weight of this structure is 2,330 kips, the negative buoyancy of the structure would be 1,600 kips. For the same wave condition, the maximum horizontal force is 430 kips. This means that a friction coefficient of 430/1,600 = 0.27 must be developed between the structure and the seafloor to resist sliding. For a sandy bottom, a friction coefficient of at least 0.5 would be expected; therefore, for this example, a factor of safety of approximately two against sliding is developed. Naturally in a silt or clay bottom, settlement of the structure and breakout forces will aid substantially in resisting horizontal movement. Additional resistance to movement would be developed by placing the structure at deeper depths and by orienting the structure so that its long axis is normal to the passing waves.

FINDINGS

1. The POL Sea Cache System is feasible in both operational and engineering aspects.

2. The POL Sea Cache System has the operational advantages of large storage capacity, mobility, rapid installation on the seafloor, and secure storage. Its disadvantage is a maximum tow speed of 10 knots when fully loaded and 13 knots when empty.

3. The concept of pre-positioning Sea Cache structures at strategic world locations enables the Sea Cache System to respond to crisis more rapidly than the currently used tanker supply system.

4. The Sea Cache System is compatible with the equipment, operations, and objectives of current and proposed POL logistic systems, such as the Marine Corp's Amphibious Assault Fuel System, the Army's Tactical Marine Terminal, and the Navy's Seaborne Mobile Logistics System.

5. A preliminary design of the Sea Cache structure resulted in a prestressed concrete, double-barreled, cross-sectional structure having the overall dimensions of 224 feet in length, 64 feet in width, and 24 feet in height. This structure can store 27,000 barrels of POL and has an operational depth of 600 feet.

6. The initial cost of a Sea Cache structure will be approximately $840,000 or $31.00 per barrel.

RECOMMENDATIONS

1. The POL Sea Cache System should undergo an in-depth feasibility study by logistic personnel to evaluate the interaction of Sea Cache with existing operations.

2. Engineering studies on a one-tenth scale model (overall length, 22.4 feet; width, 6.4 feet; and height, 2.4 feet) should be conducted to test the structural system and various towing techniques, to develop the installation and retrieval methods, and to evaluate the on-bottom stability of the structure exposed to large surface waves.

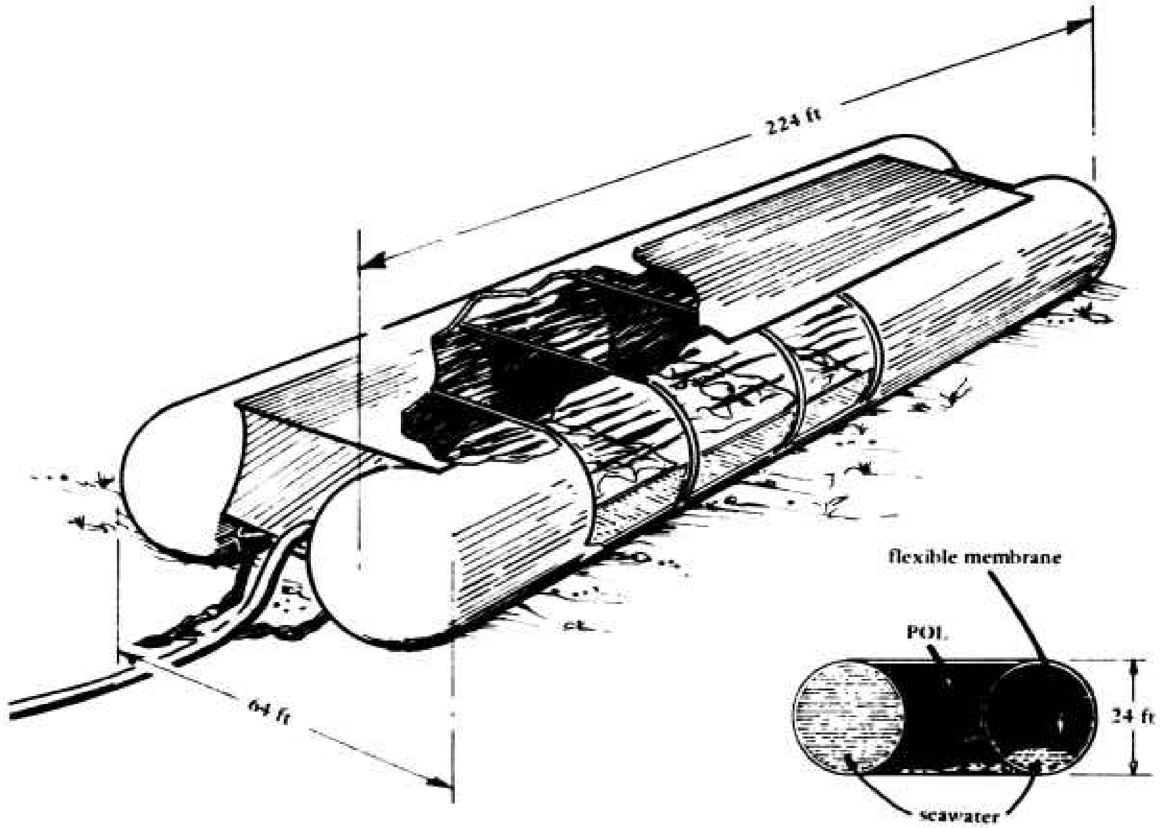


Figure 1. POL Sea Cache structure of 27,000-barrel storage capacity.

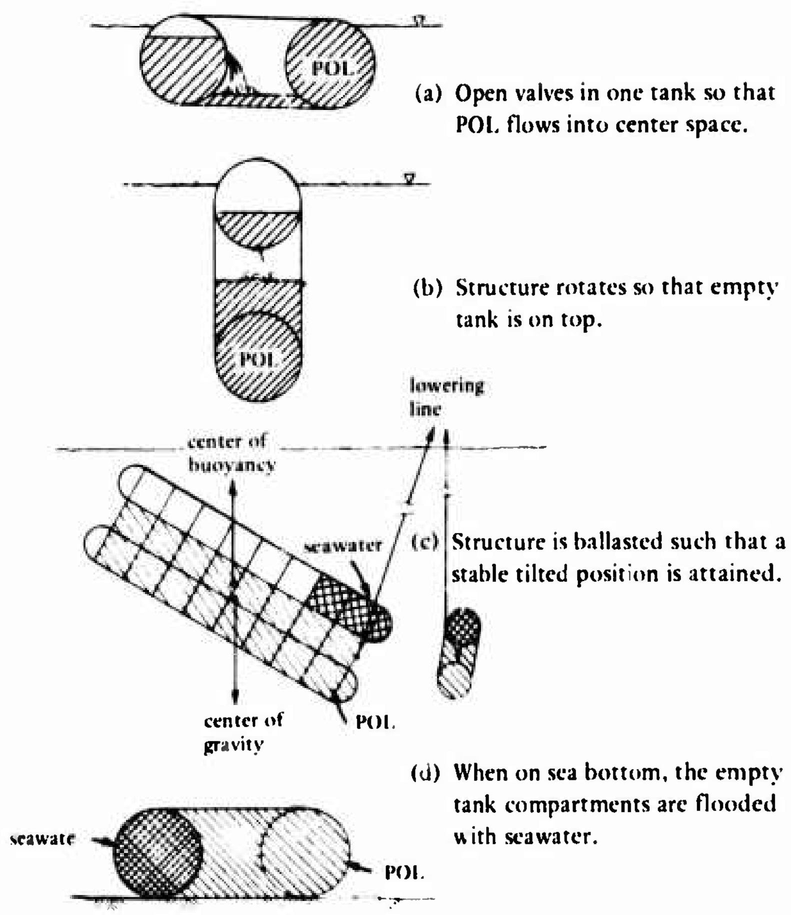


Figure 2. Deployment sequence for the Sea Cache structure.

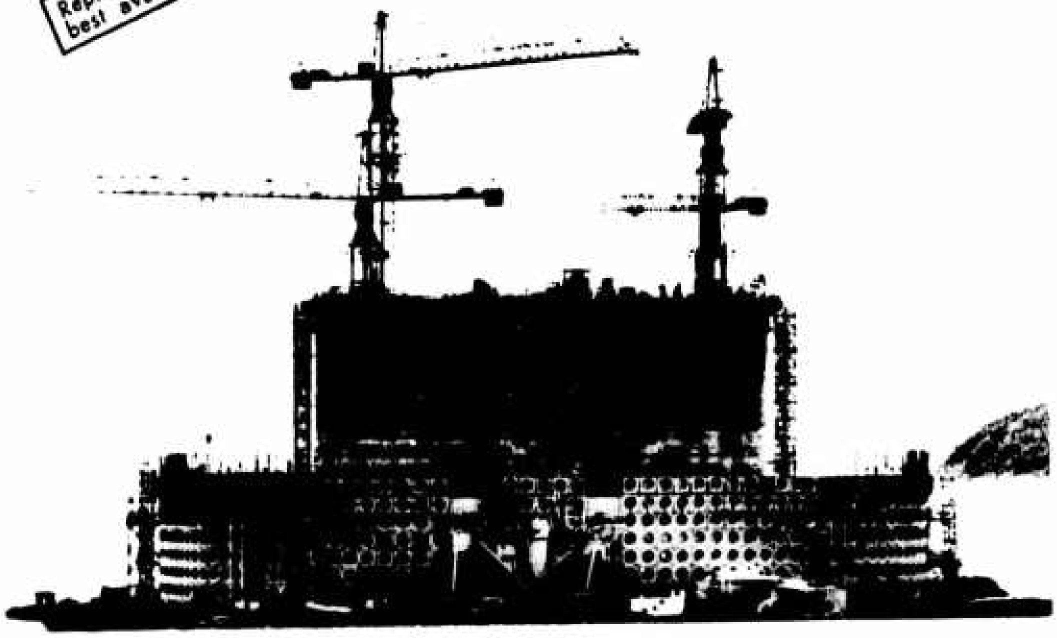


Figure 3. Ekofisk structure - a concrete crude oil storage tank.

Figure 4. Ameron Corp. concrete pipe.

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